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VERY LONG BASE LINE INTERFEROMETER (VLBI) EXPERIMENTS USING ATS-3 AND ATS-5 SATELLITES

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GSFC — GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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SUMMARY

This document is a proposal for making Very Long Base Line Interferometer (VLBI) measurements at L-band and C-band frequencies using the ATS-5 and ATS-3 satellites, respectively. The proposed experiments shall be performed jointly between the Goddard Space Flight Center (GSFC) and the Smithsonian Astrophysical Observatory. The specific objective of the proposed experiments is to evaluate the usefulness of the VLBI System as a high precision tracking technique. The system is envisioned not only as a potential tracking technique but also as a technique for the study of station location, polar-motion, continental drift and other geodetic problems.

The data collected from the proposed experiments will be used along with range and range-rate parameters to compute the orbits of ATS Satellites. Several investigative studies will be made to improve the usefulness of the technique.

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VERY LONG BASE LINE INTERFEROMETER (VLBI) EXPERIMENTS USING ATS-3 AND ATS-5 SATELLITES

I. INTRODUCTION — PROPOSED EXPERIMENT

It is proposed to make Very Long Base Line Interferometer (VLBI) measurements at L-band and C-band Frequencies using the ATS-5 and ATS-3 Satellites, respectively. The proposed experimental program is to be conducted jointly between the Goddard Space Flight Center (GSFC) and the Smithsonian Astrophysical Observatory (SAO). SAO has achieved excellent capability for conducting VLBI experiments under NASA sponsorship during the last three years. It is planned to utilize the expensive experimental apparatus developed by SAO under NASA contracts for VLBI investigations.

This program is designed to explore the potentialities of VLBI measurement techniques with both synchronous satellites (ATS) and stellar radio sources for the purposes of tracking and geodesy. The specific objective is to evaluate the usefulness of the VLBI System as a high precision tracking technique. The System is envisioned not only as a potential tracking system but also as a technique for the study of station location, polar-motion, continental drift and other geodetic problems.

The possible use of a VLBI System for navigation cannot be discounted either.

The L-band experiment using the ATS-5 satellite will be conducted during January-February, 1971, between the Agassiz Radio Observatory (SAO's facility, 40 miles north-west of Boston) and the Mojave ATSR site. The C-band experiment will be conducted during April-May, 1971 between Rosman and Mojave ATSR sites with Agassiz as a back-up third station either to take over the function of Rosman or form an independent second base line with Mojave.

VLBI techniques have been used to determine the angular sizes and positions of remote stellar objects with accuracies never before attained. The same techniques can be used to track satellites with accuracies not attained with the present techniques. Because of the angular accuracies intrinsic to the measurement, the small variations in the satellite's position will be discernible. This information is useful in the study of the dynamics of small scale motion of synchronous satellites. It is further anticipated that the VLBI data can be used to calculate ATS orbits. Since spacecraft orbit determination using VLBI technique is not yet explored, the proposed experiments shall be conducted expeditiously and with great care.

II. VERY LONG BASE-LINE INTERFEROMETER (VLBI) TECHNIQUE

a. VLBI Technique To Be Used In The Experiment

In simplest terms, an interferometer is an apparatus for measuring phase differences between electromagnetic waves received simultaneously at any two of its terminals. The Very Long Base Line Interferometer (VLBI) uses atomic frequency standards to preserve electrical phase coherence between its terminals, thus dispensing with the cables or microwave links customarily employed for this purpose. Closely regulated, but free-running and independent, these standards can be placed at arbitrarily chosen locations to allow the baselines to achieve a length of the order of several million wavelengths of the received signal. Given such ultralong baselines, wide band recording systems, low noise receivers and stable local oscillators, the VLBI systems are able to resolve signal time differences to an accuracy several orders of magnitude better than other currently available techniques.

The VLBI technique has been demonstrated by radio astronomers to have a resolving power for radio sources as low as 10^{-3} seconds of arc. The potential for measurement of angular position is correspondingly great and is now just beginning to be exploited. The adaptation of VLBI to satellite tracking therefore appears to be a highly desirable objective.

The basic measurement in radio interferometry is the relative time delay, τ_g, between two antenna for reception of a source signal. We consider the case of a satellite source. From Figure 1

$$D \cos\theta + R \cos\gamma = R + d \tag{1}$$

and

$$R \sin\gamma = D \sin\theta \tag{2}$$

Where D is the baseline dimension, γ the angle subtended at the satellite by the baseline, θ the interferometer angle at station one formed by the line of sight with baseline, and R the satellite to station two range. It follows that

$$\tau_g = \frac{d}{c} = \frac{D}{c}\left(\cos\theta - \frac{(1 - \cos\gamma)}{\sin\gamma}\sin\theta\right) = \frac{D}{c}\left(\cos\theta - \tan\frac{\gamma}{2}\sin\theta\right) \tag{3}$$

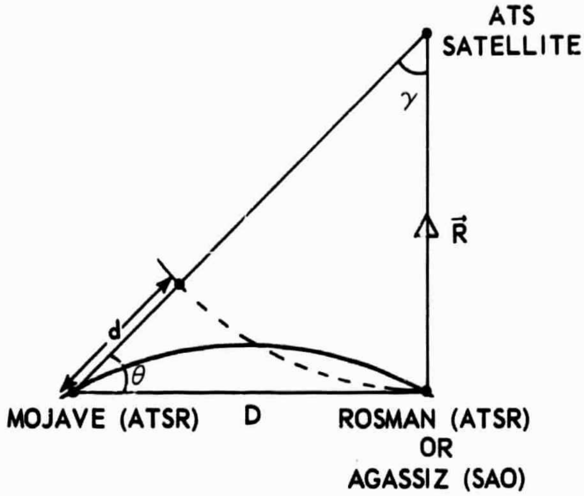


Figure 1. Geometrical Configuration of a Single Baseline Experiment

The expression for τ_g differs from that of the natural source equation

$$\tau_g = \frac{D}{c} \cos \theta \tag{4}$$

in the term dependent on γ. Using Equation (2), γ can be eliminated making τ_g an explicit function of R.

In VLBI the reduction of observations results in the production of fringes. The fringe frequency ν_F like τ_g is an observable given by

$$\nu_F = \omega \frac{d\tau_g}{dt} \tag{5}$$

where ω is the signal frequency. ν_F is a function of $\dot{\theta}$ and $\dot{R}$ as well as θ and R. So ranging observations must be incorporated in VLBI to extract θ, range-rate is needed if θ is to be extracted from ν_F. The carrier signal of the ranging system can conveniently serve for VLBI carrier signal as well.

The ATS-5 is a suitable test vehicle for VLBI experiments with a number of attractive features. The spacecraft is sufficiently remote to be seen by very long baselines. The geostationary orbit allows for continuous viewing. The signal strength is several orders of magnitude greater than that of natural sources so even greater precision is achievable. Modulation can be impressed on the signal to optimize the production of fringes, also the requirement for a broad bandwidth source is compatible with the vehicle.

With two baselines formed by three stations (like Mojave - Rosman - Santiago or Quito) the interferometry can determine a station (Rosman) to satellite direction (see Figure 2). Since we already have R and $\dot{R}$ tracking, the range vector $\vec{R}$ is determined, the range rate vector $\dot{\vec{R}}$ is similarly determined.

At the synchronous range, the VLBI precisions for arc and arc rate tracking approaches the range and range-rate tracking precisions respectively. Accordingly, the VLBI and R and $\dot{R}$ system will complement one another forming a precise vector tracking system for the ATS.

However, for the purposes of the present proposal, the geodetic (station location, polar motion, continental drift, earthquake correlation and the like) and radioastronomical (angular sizes of radiostars, mapping of radiostars, general relativity and the like) applications of VLBI will not be discussed. It should be borne in mind that the data collected can be used for the above mentioned studies.

b. VLBI State of the Art

The techniques of VLBI have been developed by radio astronomers. Hanbury Brown, et al., (1952) demonstrated an intensity interferometer without a direct real-time link between the observing stations. A physical connection between the terminals was no longer a limiting constraint on the baseline dimension.

The interferometer as a long baseline, high resolution instrument was developed at Jodrell Banks using a microwave link between the antennas. Observations were initiated in 1958. By 1967 the baseline was to ~ 130 km (Manchester) with $D = 2 \times 10^6 \lambda$.

During the mid 1960's the existence of radio sources having angular diameters as low as 10^{-3} seconds of arc was predicted. The VLBI technique was developed in the effort to resolve these sources. The feature was to introduce independent Rb atomic oscillators at the receivers as frequency and time standards. Signals were time tagged and recorded on magnetic tape for subsequent processing. The technique was successfully performed more or less simultaneously by two different experimental groups. One at UHF (Broten, et al., 1967) had a baseline

between Pentecton, British Columbia and Algonquin, Ontario, a separation of 3074 km ($D = 4.6 \times 10^6 \lambda$). The other group (Clark, et al., 1967) NRAO, operating at L-band had a baseline between Haystack and Greenbank of 845 km ($D = 4.7 \times 10^6 \lambda$).

The longest baseline over which the technique has been demonstrated is that between Goldstone and Canberra, 10,589 km operating at S-band ($D = 8.1 \times 10^7 \lambda$). The highest resolution attained is between Greenbanks and Onsala, Sweden. The operating frequency is C-band with a baseline 6,319 km ($D = 1.1 \times 10^8 \lambda$) corresponding to an angular resolution of 6×10^{-4} seconds of arc.

These investigations have demonstrated the great precision of VLBI for angular resolution. The technique entails a cross-correlation of signals from two stations and their reductions to fringes. With the rotation of the Earth the observations show changes of fringe amplitude versus projected baseline. This is the visibility curve. A decrease in visibility of fringes relates to the degree with which a source is resolved. One can then infer from decreases in visibility amplitude that the angular diameter of the source, or some component of the source, is on the order of the fringe spacing, λ / D.

The determination of the angular position coordinates has an accuracy of about one second of arc or somewhat better. This has not yet approached the level of precision being achieved in angular resolution. Although fringe amplitude is accurately measured, adequate phase data is lacking.

Uncertainties in interpretation arise from the large fringe-rates (of the order of KHz) that are normally observed. The uncertainty is in the form of difficulty in determining on which fringe the source is on at a particular time. This difficulty can be overcome by deliberately off-setting the local oscillator frequency in order to lower the fringe-rate so that the individual fringes could be seen above noise.

Position determination depends directly on the measurement of time-delay, τ_g. The accuracy of τ_g in turn depends on having a broad bandwidth source and a capacity for processing over a sufficiently wide bandwidth in the cross-correlation of signals. We will describe how bandwidth considerations enter in the determination of τ_g.

The VLBI technique has been referred to as both an independent clock interferometer and as a correlation interferometer. The signal and data processing at the two stations are controlled by independent hydrogen masers and frequency standards). Incoming signals of frequency ω are precisely time tagged and heterodyned with a local oscillator frequency ω_0 to the video frequency $\omega - \omega_0$.

The signal is converted to digital form by clipping. The loss in signal to noise ratio, $2/\pi$, is compensated by increased efficiency and capacity in the data processing. For economy in storage the clipped signals are sampled in accord with Nyquist theorem at twice the video recorder bandwidth and the time encoded data is transferred to magnetic tape. The records are subsequently brought together in a digital computer for cross-correlation and reduction to fringes.

The significance of bandwidth is recognized by first noting that for a monochromatic signal the correlator output is

$$R(\tau_c, \tau_g) = \left[\cos\ (\omega - \omega_0)\ \tau_c - \omega \tau_g + \theta\right] \tag{6}$$

where τ_c is the correlation time and θ is an unknown instrumental phase difference introduced between the two stations. It is clear that τ_g can not be precisely deduced due to the presence of θ. For a wide bandwidth signal the cross-correlation function becomes

$$R(\tau_c, \tau_g) = \Delta\omega \cdot \frac{\sin \Delta\omega(\tau_c - \tau_g)}{\Delta\omega(\tau_c - \tau_g)} \cos\ (\omega_0 \tau_g - \theta) \tag{7}$$

where $\Delta\omega$ is the recorder bandwidth. The uncertainty in determining τ_g decreases with increasing bandwidth as $(\Delta\omega)^{-1}$. Most recorders used in VLBI are adaptions of the commercial type with video bandwidth of 360 kHz. Recently recorders have been developed and tested which have an effective bandwidth of 20 MHz. These selectively sample discrete narrow bands equally spaced across a broad bandwidth. The precision for τ_g with this recorder is, depending on the signal to noise ratio, $\sim 10^{-8}$ sec.

Experimenters in VLBI have used Loran-C signals for synchronizing of station clocks. The accuracy of the system is dependent on the time delay for reception of the 100 kHz signal from the Loran transmitter. When the two are in close proximity accuracy on the order of a microsecond is achievable. This is tolerable as an initial time error in the bit by bit cross correlation of the recorded data.

Time synchronization by signal exchange between stations via satellite is capable of high precision. This would eliminate the cumbersome procedure of transporting clocks between stations.

Synchronization of clocks is also possible with a stellar source if both source position and baseline dimensions are accurately known. The relation for errors in source position, $\Delta\theta$, baseline dimension, ΔD, and clock alignment, Δt is given by

$$\Delta t = \frac{\Delta D \cos\theta}{c} - \frac{D(\Delta\theta)\sin\theta}{c} \tag{8}$$

For $\Delta\theta \sim 0.1''$, and $\Delta D \sim 1$ meter, then $\Delta t \sim 10^{-8}$ sec. The clock synchronization is achieved when the signal observations are reduced and the fringes optimized. Correction for atmospheric propagation delay effects must be applied to τ_g.

The output data of the VLBI processor is $\tau_g(t)$. For the tracking of natural sources

$$\tau_g(t) = A + B \sin(\omega_e t + \phi) \tag{9}$$

where ω_e is the Earth's angular velocity and A, B, and ϕ are three known numerical parameters. The baseline vector and source position constitute five parameters to be determined. By tracking three different sources the number of known and unknown is nine. The coordinate positions can then be determined.

c. VLBI Tracking Methods

Very long baseline interferometry (VLBI) is recognized as an ultra-precise technique for the measurement of angles. This is a brief note describing how VLBI can be applied for satellite tracking.

One method for tracking is based on the familiar form of the interferometer equation modified to incorporate a station to satellite range. In order to extract angle data from interferometric observations, range measurements must also be performed. In this respect ranging must be regarded as an integral part of this VLBI tracking method.

There is another way in which VLBI observations can be used for determining a satellite position without introducing range measurements. This involves three independent baselines formed by four stations. We outline the basic scheme for both methods.

c-1. Range-Vector Tracking—The VLBI makes simultaneous measurements on a satellite signal at widely separated stations. The observed signals are essentially replicas of one another except for a geometric time delay, τ_g, in the reception. The determination of τ_g involves time tagging the received signals with a hydrogen maser clock and recording the processed data on magnetic tape. Subsequently the tapes from both stations are combined in a computer and τ_g is deduced.

The expression for the time delay is

$$\tau_g = \frac{R_1 - R_2}{c} \tag{10}$$

where R_1 and R_2 are station to satellite range (Figure 2) for the respective stations and c, the speed of light. From the geometry

$$R_1 - R_2 = D \cos\theta_1 + R_2 \cos\gamma - R_2 \tag{11}$$

and

$$R_2 \sin\gamma = D_1 \sin\theta_1 \tag{12}$$

Substituting Equations (11) and (12) into (10) gives

$$\tau_g = \frac{D_1 \cos\theta_1 + \sqrt{R_2^2 - D_1^2 \sin^2\theta_1} - R_2}{c} \tag{13}$$

The measurement of the satellite range R_2 is needed to deduce the angle θ_1. By making station #1 the terminal of a second baseline, the angle θ_2 that the vector $\vec{R}_1$ forms with baseline can similarly be determined. This fixes the direction of $\vec{R}_1$. With ranging observation at #1, the satellite range vector $\vec{R}_1$ is determined.

Thus the VLBI technique with three observing stations, combined with ranging observations forms a range vector tracking configuration.

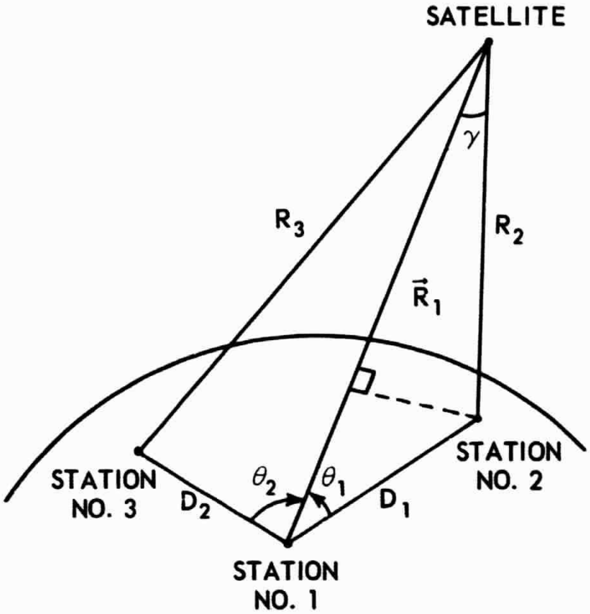


Figure 2. Three Station Configuration

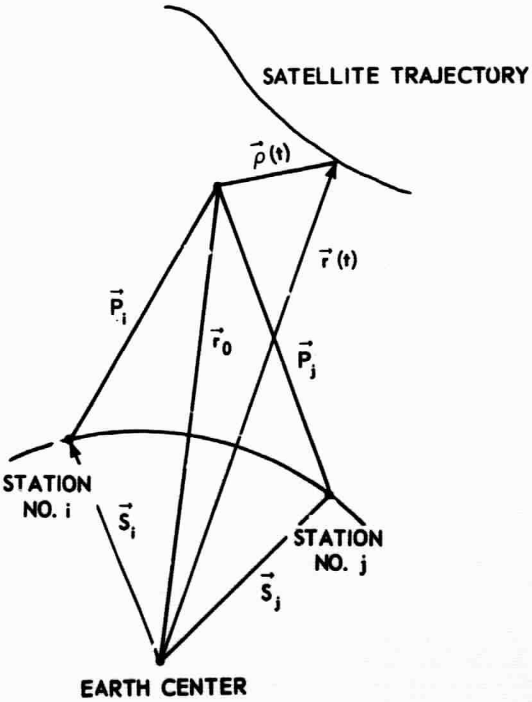


Figure 3. Satellite Trajectory

c-2. Trajectory Determination Method—Here we write Equation (10) as can be derived from Figure 3,

$$\tau_{ij}(t) = \frac{|\vec{r}(t) - \vec{S}_i| - |\vec{r}(t) - \vec{S}_j|}{c} \tag{10A}$$

where $\vec{r}(t)$ is the satellite position vector and $\vec{S}_i$ and $\vec{S}_j$ are positions of the baseline terminals relative to the earth center. Station positions are assumed to be known. The analysis has been done using earth fixed coordinate system. There are to be three independent baselines formed by four stations. By fitting a polynomial to the observed $\tau_{ij}(t)$, we can determine

$$c\tau_{ij}(t) = A_{ij} + B_{ij}t + C_{ij}t^2 + \ldots + L_{ij}t^n \tag{11A}$$

We are to determine the satellite trajectory $\vec{r}(t)$ from the three sets of coefficients given in Equation (2).

Let $\vec{r}_0$ be a given point (determined by conventional tracking method) which is within several hundred meters of trajectory intervals over which observations are made. Then define

$$\vec{\rho}(t) \equiv \vec{r}(t) - \vec{r}_0 \tag{12A}$$

Now Equation (10A) becomes

$$\tau_{ij} = \frac{|\vec{r}_0 - \vec{S}_i + \vec{\rho}(t)| - |\vec{r}_0 - \vec{S}_j + \vec{\rho}(t)|}{c} \tag{13A}$$

or

$$\tau_{ij} = \frac{|\vec{P}_i + \vec{\rho}(t)| - |\vec{P}_j + \vec{\rho}(t)|}{c} \tag{14A}$$

where

$$\vec{P}_i \equiv \vec{r}_0 - \vec{S}_i \quad \vec{P}_j \equiv \vec{r}_0 - \vec{S}_j$$

are constant vectors of nominally 3.5×10^4 km in length for a near synchronous satellite.

Next we make the expansion

$$|\vec{P}_i + \vec{\rho}(t)| = P_i + \frac{\vec{P}_i \cdot \vec{\rho}}{P_i} + \frac{\rho^2}{2P_i} - \frac{(\vec{P}_i \cdot \vec{\rho}_i)^2}{2P_i^3} + \ldots \tag{15A}$$

Inserting into Equation (14A) we have

$$c\tau_{ij} = P_i - P_j + \left(\frac{\vec{P}_i}{P_i} - \frac{\vec{P}_j}{P_j}\right) \cdot \vec{\rho} + \rho^2 \left(\frac{1}{P_i} - \frac{1}{P_j}\right) - \frac{1}{2}\left\{\frac{(\vec{P}_i \cdot \vec{\rho})^2}{P_i^3} - \frac{(\vec{P}_j \cdot \vec{\rho})^2}{P_j^3}\right\} + \ldots \tag{16A}$$

We make the approximation of retaining terms to first order in $\vec{\rho}(t)$. Thus we write

$$c\tau_{ij} = P_{ij} + \vec{u}_{ij} \cdot \vec{\rho}(t) \tag{17A}$$

where

$$P_{ij} = P_i - P_j \tag{18A}$$

and

$$\vec{u}_{ij} = \frac{\vec{P}_i}{P_i} - \frac{\vec{P}_j}{P_j} \tag{19A}$$

Now, quite generally

$$\vec{\rho}(t) = f_x(t)\,\hat{i} + f_y(t)\,\hat{j} + f_z(t)\,\hat{k} \tag{20A}$$

and

$$\begin{aligned} f_x &= a_x + b_x t + c_x t^2 + \ldots \\ &\quad \ldots \\ f_z &= a_z + b_z t + c_z t^2 + \ldots \end{aligned} \tag{21A}$$

Inserting Equations (20A) and (21A) into (17A) gives

$$\begin{aligned} c\tau_{ij} = {} & P_{ij} + u_{ij,x}\,a_x + u_{ij,y}\,a_y + u_{ij,z}\,a_z \\ & + (u_{ij,x}\,b_x + u_{ij,y}\,b_y + u_{ij,z}\,b_z)\,t \\ & + (u_{ij,x}\,c_x + u_{ij,y}\,c_y + u_{ij,z}\,c_z)\,t^2 \\ & + \ldots \end{aligned} \tag{22A}$$

Identifying Equations (22A) and (21A) we finally have

$$\begin{aligned} A_{1,2} &= P_{1,2} + u_{1,2,x}\,a_x + u_{1,2,y}\,a_y + u_{1,2,z}\,a_z \\ A_{2,3} &= \ldots \\ A_{3,4} &= P_{3,4} + u_{3,4,x}\,a_x + u_{3,4,y}\,a_y + u_{3,4,z}\,a_z \end{aligned} \tag{23A}$$

$$B_{1,2} = u_{1,2,x}\, b_x + u_{1,2,y}\, b_y + u_{1,2,z}\, b_z$$

$$B_{2,3} = \quad . \quad . \quad . \tag{23A}$$

$$B_{3,4} = u_{3,4,x}\, b_x + u_{3,4,y}\, b_y + u_{3,4,z}\, b_z$$

The Equation (23A) forms sets of three simultaneous independent equations for determining the n sets of coefficients of Equation (21A).

Thus $f_x(t)$, $f_y(t)$, and $f_z(t)$ are determined. So also are $\vec{\rho}(t)$ by Equation (20A) and finally $\vec{r}(t)$ by Equation (12A). It should be noted that the requirement of four stations is necessary. For three baseline and three stations the τ_{ij} are redundant.

The error in $\vec{r}(t)$, denoted Δr, due to the approximation entailed in Equation (17A) is given by

$$\frac{\Delta r}{I} \sim I/P$$

where I is the length of the trajectory interval covered by Equation (11A) and $P = 3.5 \times 10^4$ km. For $I = 6$ km, $\Delta r \sim 1$ meter. For $I = 10$ km, $\Delta r \sim 3$ meters. If we assume a mean satellite speed over the interval I, then 10 km corresponds to an approximately 8 minute orbit arc. This appears to be a reasonable useful tracking interval.

It furthermore appears that long arcs could be segmented into shorter ones giving exceptable accuracies.

c-3. VLBI Capabilities—It is possible to specify theoretically the capabilities of a VLBI system assuming that (a) the station time synchronization is achievable to an accuracy of 0.05 μsec, (b) the time-delay resolution can be made to within 0.01 μsec, and the fringe frequency resolution is within 3×10^{-3} Hz. These accuracies have been achieved in the past experiments. The following table (Table 1) compares the VLBI tracking system with the best of the current systems.

Table 1

Comparison of VLBI and Other Tracking Systems

Tracking Parameter	VLBI System	Current Systems
Angular Resolution ($\Delta\theta$)	5×10^{-8} radians	2×10^{-5} (minitrack)
Arc Resolution ($\Delta S = R\Delta\theta$)	2 meters	Not measured
Angular Rate Resolution ($\Delta\dot{\theta}$)	2×10^{-11} radians/sec	Not measured
Arc Rate Resolution ($\Delta\dot{S} = R\Delta\dot{\theta}$)	0.7 mm/sec	~ 1 mm/sec (Range-Rate Only!)

d. VLBI Experiments With Synchronous Satellites

d-1. Review of Past Work—The VLBI experiment performed by the MIT experimenters with the wideband TACSAT satellite system seems to have confirmed the validity of the technique even though no detailed analysis of the data has been reported. Smithsonian conducted a VLBI experiment during the early part of 1970 with the ATS-5 satellite L-band transponder using the Agassiz, Massachusetts - Owens Valley, California baseline. They have been able to obtain correlated fringes for various signal modulations. The correlation function and spectrum have been analyzed for various modulation schemes. The analysis has shown promise of giving good positional accuracy when the modulation of the signal is optimized. However, due to the limited scope of the investigations, SAO has not embarked on an extensive experimental and data analysis program. Our proposed experiment to be conducted in collaboration with SAO will be the first comprehensive experimental and data analysis program to test the feasibility of using VLBI data for tracking purposes. We plan to be able to optimize the modulation schemes after testing several (PSK, FM, PM and the like) modulations. A data processing facility shall be set up to handle vast quantities of VLBI data with relative ease and economy.

Sensitivity tests with different correlation lengths of the received signals, various spacecraft-transmitter power levels, or controlled antenna-pointing offsets would be valuable in the determination of minimum performance specifications for equipment to be designed solely for satellite-source VLBI.

d-2. Proposed VLBI Experiments With ATS Satellites—VLBI has a number of applications for geodesy and geophysical phenomena. The strong signals of

synchronous satellites can be used to conduct remote site geodetic surveys with portable low gain receiving antennas. Long term observations on natural sources have a potential for detecting continental drift, variations in the rate of rotation of the Earth, and polar motion. However, a parallel displacement of a baseline is not detectable through natural source observations. The tracking of synchronous satellites by virtue of their finite range may show not only the horizontal movement of continental blocks, but also the diurnal heaving of the Earth due to tidal action.

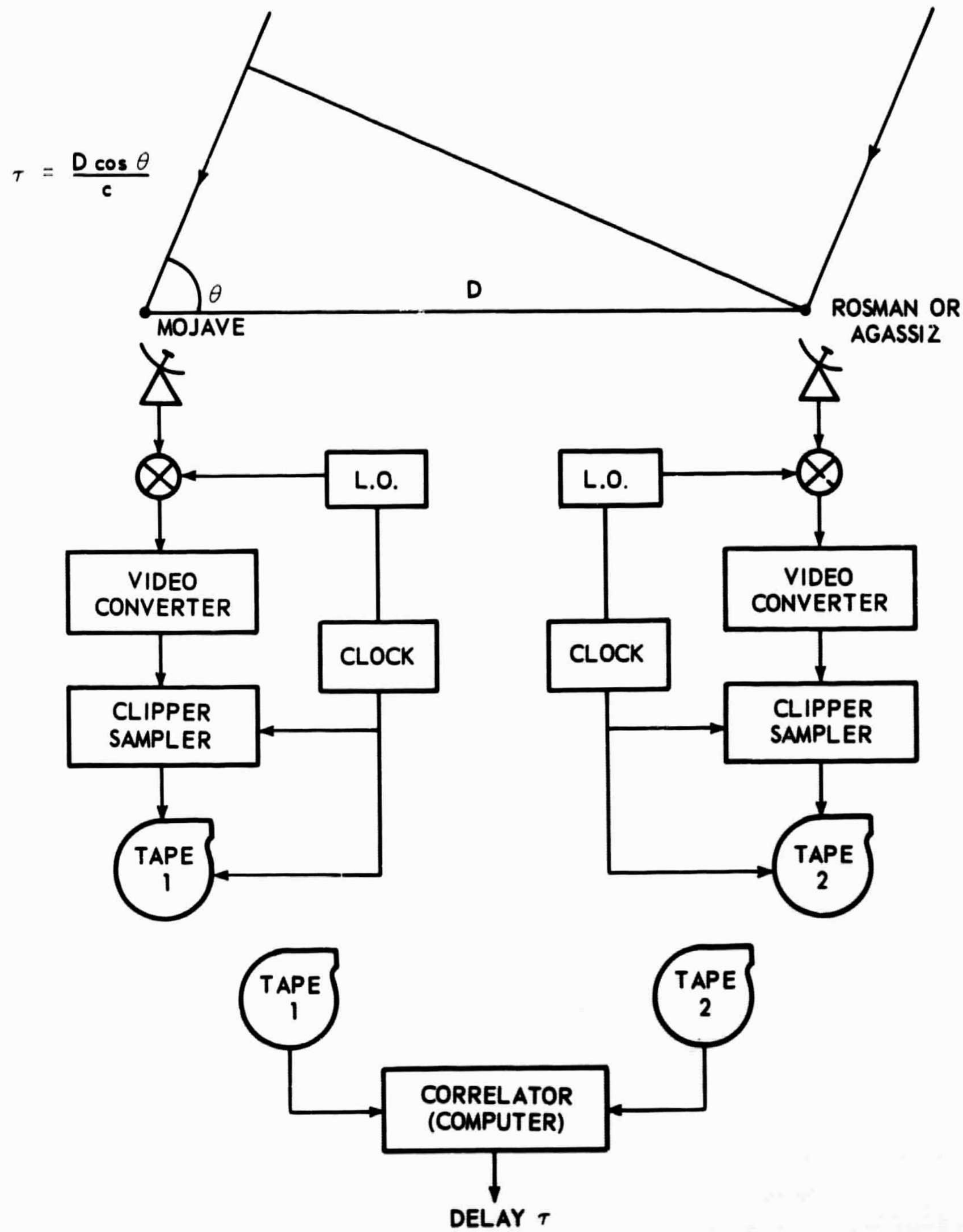
Atmospheric effects must be corrected in the precise determination of time delay. Indeed the limitations for atmospheric correction may determine the threshold for detecting geophysical processes. Real-time, line-of-sight probing of both the troposphere and ionosphere is necessary to achieve the highest sensitivity. For C-band the tropospheric effects will predominate over the ionospheric effects, while at L-band the ionosphere effects may predominate.

III. DESCRIPTION OF THE EXPERIMENT

Figure 4 is a schematic of a single baseline interferometer system. Independent but identical VLBI backends are used at each terminal for the recording of data. The SAO VLBI backends are built to receive 30 MHz IF at the first stage local oscillator mixer from the antenna front end. At Agassiz (SAO station), the 85' dish with a modified feed will be used to receive the L-band signals. There is a 30 MHz IF available at the output of the antenna front-end unit. Therefore, the SAO VLBI backend can be used at Agassiz without any modification.

At Mojave, for the L-band experiment, there is a need to interface with the existing L-band system at Mojave. Also, all ATSR stations have a standard IF output of 70 MHz. There is a need to derive a 30 MHz IF from it without disrupting the normal operational capabilities of the Mojave ground station. We may recall, in this context, that the L-band experiment will be done using the Mojave-Agassiz baseline. Figure 5 shows a detailed block diagram of the Mojave L-band front end and the SAO VLBI backend. Also shown are the proposed modifications (shown in broken lines).

As seen above, the only changes needed are (1) the VLBI Frequency Standard (Hydrogen Maser or Rubidium Standard) will drive the Mojave front end local oscillator circuits, (2) the 100 MHz signal available in the Mojave system will be tapped using suitable isolators and filters to mix with the available 70 MHz IF in order to obtain the 30 MHz IF required for the SAO VLBI backend. These are minor modifications and the interconnections will be made in such a way that



VERY LONG BASELINE INTERFEROMETER

Figure 4. Very Long Baseline Interferometer

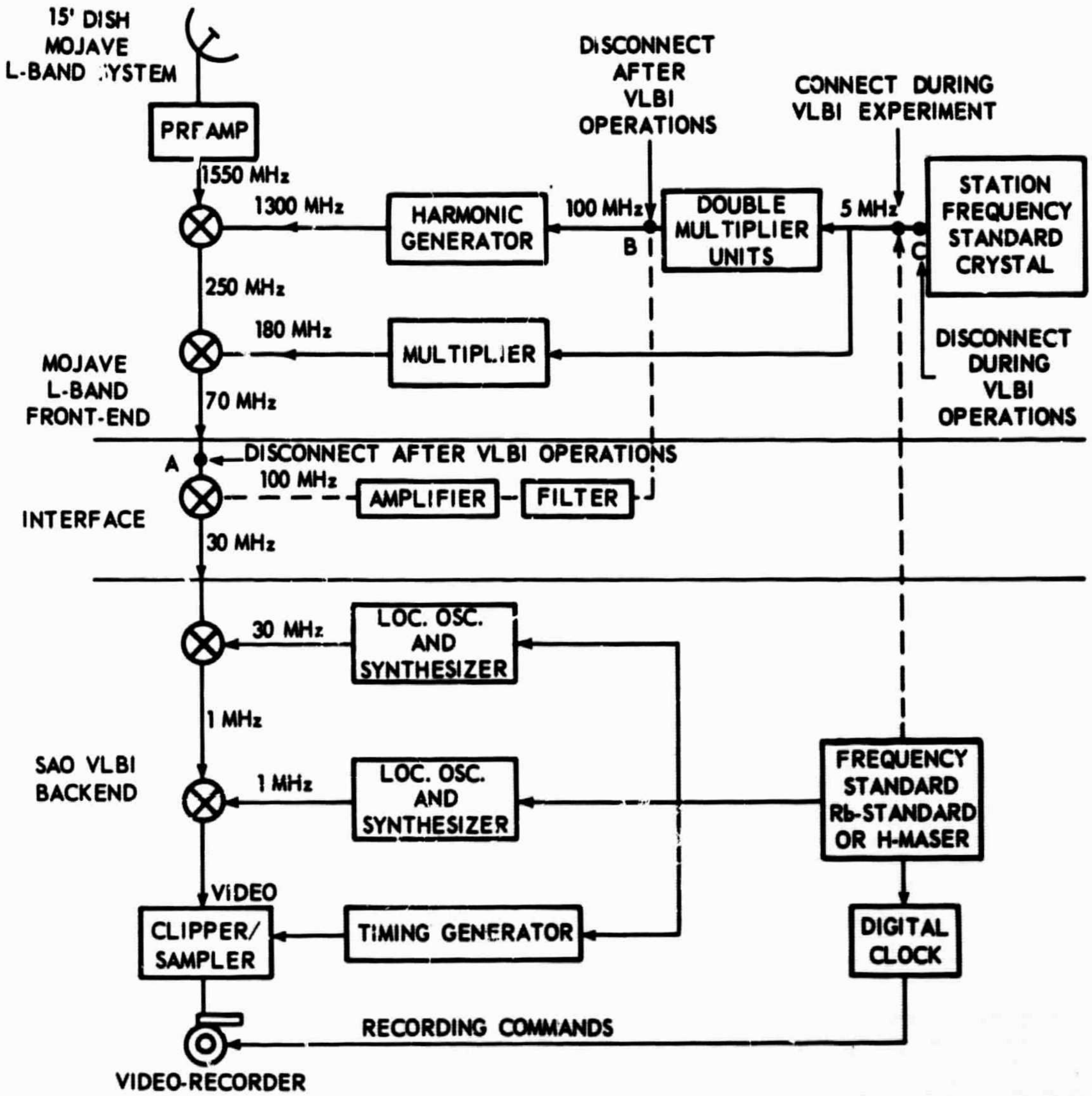


Figure 5. Schematic Diagram of Mojave (ATSR) L-Band Front End Interface With the VLBI Backend and Recording Systems

they can be disconnected momentarily and turn the station back to normal operation.

In the ATS-3 C-band experiment to be done between Mojave and Rosman, a slightly different approach will be used to derive the 30 MHz IF needed for the SAO VLBI backends. However, the backends are identical to the ones to be used in the L-band experiment. The modification to be used is shown in Figure 6.

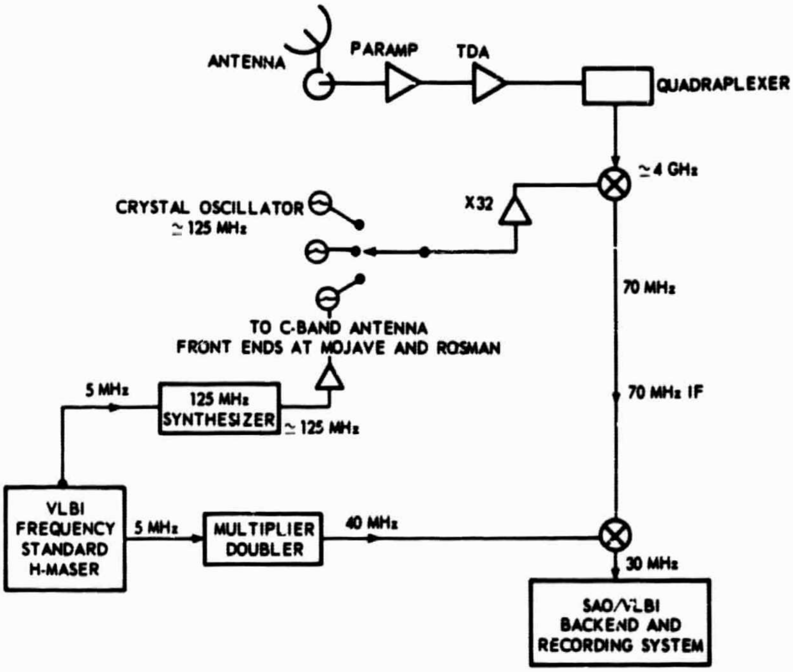


Figure 6. Schematic Diagram of Mojave (ATSR) and Rosman (ATSR) C-Band Front End Interface With the VLBI Backend and Recording Systems

The recording system that will be used in the experiments is shown schematically in Figure 7. A video-recorder is used to record the data.

In the play-back system, the video-data recorded at each terminal is transformed into 9-track digital recording on magnetic tapes. Video data tapes, are reformatted and transcribed onto 9-track digital tapes at the SAO Computer Facility in Cambridge, Massachusetts. The schematic of the play-back system is shown in Figure 8. The tapes from the two stations are then correlated using a special purpose correlator/computer setup.

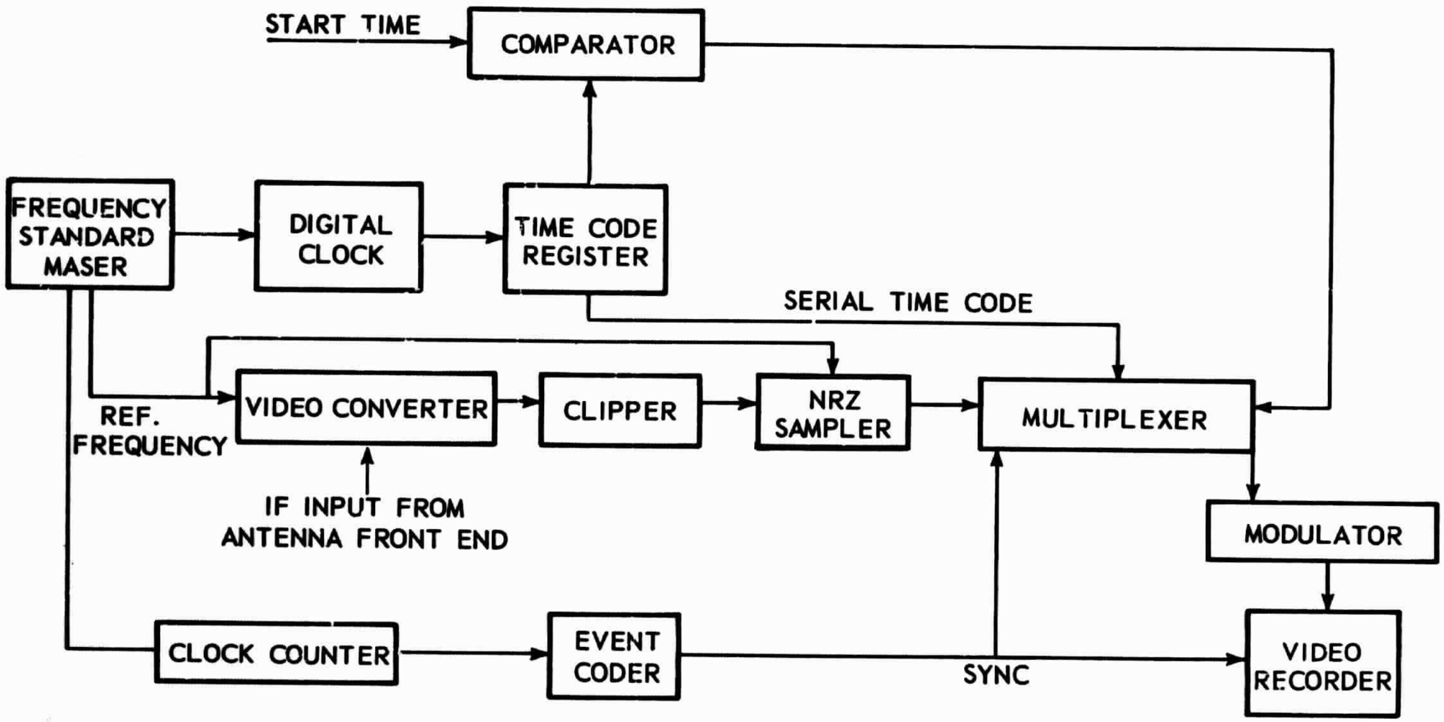


Figure 7. Video Recording System

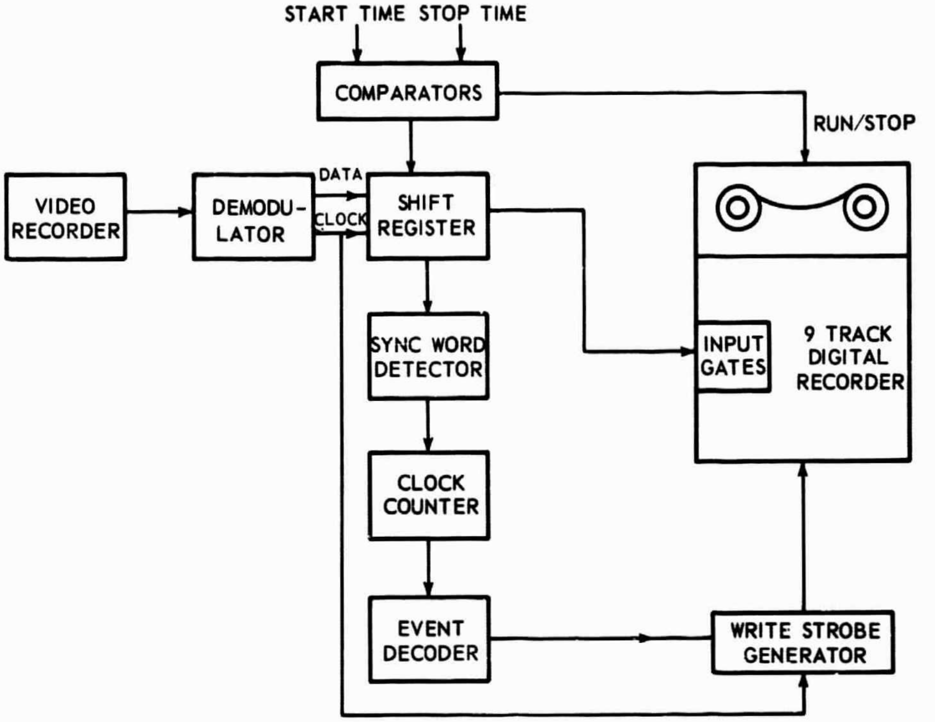


Figure 8. Video Playback and Data Formatting System

The recording medium at each station is a video magnetic tape which is used in a helical scan recorder. This allows continuous recording of data. One bit video recording backends with sampling rates of 714, 720 and 920 K bits/sec developed by SAO will be used in the experiment.

Sufficient number of frequency standards (hydrogen masers and rubidium frequency standards) will be maintained during the experimental program. System clock times at each station are set by portable cesium units.

The spin-rate of ATS-5 satellite is not expected to cause any problem. It will only reduce the relative magnitude but not the shape of the correlation function generated over the length of the cross-correlation period. The data would show a 1 Hz amplitude modulation of the transmitted signal. It could be recovered by maximizing the length of the correlation period.

IV. EXPERIMENTAL PLAN AND SCHEDULE

a. Tan Description

Goddard Space Flight Center in collaboration with the Smithsonian Astrophysical Observatory will conduct a program of experimental measurement and supporting analyses in order to develop the use of ATS-3 and ATS-5 satellites as satellite-borne radio-sources in Very Long Base Line Interferometry. The experimental program will be for a period of six (6) months beginning January 1, 1971. The tasks to be accomplished during this period will be as follows:

a-1. We shall become acquainted with the ATSR ground station operations to the extent that is needed to conduct satellite VLBI measurements at these stations. Design specifications of the spacecraft transponders (onboard ATS-3 and ATS-5) and the antenna patterns will be studied. It should be mentioned that we have already achieved familiarity with the command, tracking and data acquisition equipments at the ATS and STADAN stations.

a-2-1. During the months of January and February, a VLBI experiment will be conducted using the Agassiz (SAO) - Mojave (ATSR) baseline and the ATS-5 L-band transponder as a radio-source. SAO VLBI backends and recording equipment will be used in the experiment. SAO will also provide all the interconnections and specifications in advance to allow smooth interface of the experiment at the ATSR ground stations. The experiment will be done 2 hours per day, five (5) days a week for four (4) weeks. The two hours of experimental time will be staggered over the eight (8) hours operating time of the station. Once during the experiment, the measurements will be coordinated with the Applied Information Industries (AII) L-band experiment to obtain 15 minutes of data every hour for 24 hours. The ATSR L-band transmitting equipment at Mojave will be used to transmit specific modulated signals to the satellite. Various types of signal modulations will be used in the experiment. The optimum signal modulation should produce the most resolvable and unambiguous cross correlation product at the correlator output. Modulations of the type (a) constant density noise, (b) set of harmonically related sidetones, (c) pseudo-random binary coded character sequences, (d) narrow-band FM or PM modulation will be tried during the experiment.

It is felt that the VLBI experiment will not have any adverse impact on any of the planned experiments at the ATSR ground sites. No unusual power or operational requirements are called for and the experiment will be performed within the normal operational capabilities of the ATSR stations. As described in the description of the experiment, no ATSR ground station

equipments are required except the normal facilities at Mojave and Rosman to install the SAO VLBI backends and interface connections. ATSR ground support is requested to provide signal transmissions to the satellite with predetermined modulation sequences. In the receiver part, the 70 MHz IF will be used to input the VLBI system. All the interface requirements specified by the ground stations will be strictly adhered to. The VLBI equipment will be interconnected with the Mojave (and Rosman) front end in such a way that it can be disconnected momentarily to allow the ground stations to operate normally.

The atomic frequency standard (rubidium standard or hydrogen maser) used to drive the VLBI backend will also be used to replace the ATSR station frequency standard (crystal) to drive the front end down-converter circuit during the experiment.

It is requested that the ATS project provide range and range rate raw data in paper tape form from the two stations Rosman and Mojave. The data sampling rate shall be 6 samples per minute.

Ionospheric and tropospheric time-delay corrections to the VLBI data will be obtained by independent experiments. Faraday rotation experiment, simultaneous VHF/C-band ranging experiment are two of the techniques which the Mission and Trajectory Analysis Division has used successfully to derive ionospheric parameters. These techniques will be employed by us using the same satellites. Tropospheric time-delay corrections will be accomplished by measuring surface refractivity as a function of time by wet and dry-bulb technique. This technique has been used by us successfully in the past.

<u>a-2-2</u>. The video tapes will be processed at SAO. The data on the video tapes (a 2" wide 5550 feet long tape will record up to 5 hours of data) will be reformatted and transformed on to 9 track digital tapes. A 2400 feet long magnetic tape will record up to 4 minutes of reformatted VLBI data.

<u>a-2-3</u>. The data from both Agassiz and Mojave will be matched tape by tape with correlated time. Then the data tapes from the two stations will be cross-correlated using the SAO CDC-6400 Computer/Cross-Correlator System. The correlation function amplitude and spectrum will be studied to identify optimum modulations. Preliminary analysis of data will be done at SAO to insure the quality of data. From time to time, SAO will perform detailed analysis with the reduced data to recover time delays and fringe frequencies as a function of time.

a-2-4. The digital magnetic tapes are processed in detail at GSFC using the available computer facilities (which are extremely compatible and adequate for our purposes) to study such parameters as signal time-delay and fringe frequency as a function of time. Suitable analytical models will be used to transform these parameters to spacecraft coordinates. A covariance analysis including all variables is made to estimate error magnitudes in the determined ATS position coordinates.

a-2-5. It is planned to develop comprehensive data-analysis capability at GSFC with the help of the Smithsonian Astrophysical Observatory. Work has already begun in the Mission and Trajectory Analysis Division towards developing analytical models for relating VLBI parameters (time-delay, fringe-frequency) to significant tracking parameters (position coordinates, orbits) using such accessory information as range, range rate, station positions and the like.

a-2-6. Smithsonian has developed several computer programs towards the accomplishment of tasks described above. At GSFC, we are developing additional computer programs to relate VLBI data with tracking and geodetic parameters.

a-2-7. The analysis and interpretation of data will be done jointly by GSFC and SAO personnel.

a-2-8. ATS project will provide operational support for the experiment. All the data and results of the experiment will be submitted to the ATS Project Office for review.

a-3. During April-May, 1971, another VLBI experiment will be performed using Rosman (ATSR) and Mojave (ATSR) baseline and the ATS-3 C-band transponder as the radio-source. The operational details will be similar to those of the first experiment described earlier. SAO's role as contractor will be maintained and the SAO VLBI equipment will be used in this experiment also.

a-4. We will conduct supporting analytical studies in a number of areas that show promise in satellite-oriented VLBI experiments. These areas include such topics as (1) the coding and modulation of transmitted signals to improve VLBI system performance by identifying new signal modulation techniques, (2) conduct sensitivity tests with different correlation lengths of the received signals, various spacecraft-transmitter power levels and controlled antenna-pointing offsets that are useful for minimum performance specifications for VLBI equipment, (3) conduct design studies for a special purpose correlator capable of handling bandwidths up to 2.0 MHz - 10.0 MHz. Monitoring relatively

narrow-band frequency windows (1-2 MHz) over a wide band (10 to 20 MHz) gives a wide effective bandwidth which in turn improves the system resolution, (4) conduct studies on various modulation techniques to recover range information when one of the terminals of a baseline and the ground transmitting station are colocated (for example, Mojave), (5) consider the possibility of using returned radiation together with the usual satellite range data to correct for atmospheric delay effects on the VLBI signals.

One other area of investigation on which major efforts will be made is towards development of an orbit computation scheme using spacecraft coordinates obtained by single baseline and/or double baseline interferometry.

b. Role of the Smithsonian Astrophysical Observatory (SAO) In The Proposed Program

b-1. Justification—The proposed VLBI experiments and analyses will help to explore the full potential of VLBI techniques (both satellite-oriented and natural radiosource) for tracking and geodesy. NASA should take an active and timely role in the investigation of the full potentials of this high precision technique. SAO has developed excellent capability (both experimental and analytical) under NASA sponsorship to make VLBI measurements and interpretation. The total investment in equipment alone is well over a quarter of a million dollars. Besides, SAO has extensive data gathering and analysis experience in tracking and geodesy. It is logical to utilize the existing equipment and expertise of SAO from the point of view of time, economy and major objectives of the program. We therefore recommend that our program be carried out in collaboration with the Smithsonian Astrophysical Observatory and a contract be awarded to SAO to provide the necessary support.

b-2. Statement of Work—SAO shall perform the following tasks if a contract is awarded to them:

b-2-1. Provide interface design and fabrication for Agassiz-Mojave (L-band/ATS-5) and Rosman-Mojave (C-band/ATS-3) experiments.

b-2-2. Provide data acquisition including instrument installation, handling and training (of GSFC and ATSR personnel).

b-2-3. Conduct Mojave/Agassiz L-band experiment using ATS-5 for a period of 4 weeks during January-February 1971.

b-2-4. Conduct Mojave/Rosman C-band experiment using ATS-3 for a period of 4 weeks during April-May 1971.

b-2-5. Prepare reformatted data on digital magnetic tapes preparatory to analysis.

b-2-6. Conduct computer correlation of the VLBI data at the SAO Computer Facility to determine (a) the operational requirements of the experiment, (b) the quality of data and (c) elimination of spurious data from the video tapes.

b-2-7. Assist in the data analysis operations at GSFC.

b-2-8. Assist in the VLBI data reduction in order to obtain spacecraft position coordinates using baseline parameters and signal modulation characteristics. Range and range rate data to be supplied by the ATSR facilities will also be used in the analyses.

b-2-9. Prepare a final report on the experiments and associated data analysis.

b-3. Experimental Equipment To Be Supplied By SAO—The equipment to be furnished by SAO for the proposed experiments shall consist of such items as

b-3-1. At least two atomic frequency standards (Rb standards and/or hydrogen masers) for each experiment. At least one standard should be located at each terminal of a baseline.

b-3-2. Frequency distribution systems, VLBI clocks, data modulator/formatter equipment, video recorders, interconnecting cables, regulators, VLF tracking receivers and recorders, LORAN-C visual type systems, video converters, sampler/clipper systems, portable clocks, filters, isolators, amplifiers and mixers.

b-3-3. Data reformatting system for translating reformatted video data on to 9-track digital magnetic tapes.

b-3-4. Computer facilities for the reduction of VLBI data on 9-track digital tapes.

b-4. Personnel—SAO shall furnish sufficient manpower for satisfactory performance of tasks outlined above.

c. Facilities and Personnel Requirements At Goddard Space Flight Center

Personnel and facilities of the Mission and System Analysis Branch, Mission and Trajectory Analysis Division, Tracking and Data Systems Directorate of

the Goddard Space Flight Center are adequate for satisfactory accomplishment of the tasks outlined in the proposed program. The GSFC Computer Facility is adequate for VLBI data processing. Operational support of ATS Ground Support Office is requested. No unusual constraints or requirements are placed by the posed program on the normal operations of the ATS satellite and other operating GSFC programs.

Dr. Jayaram Ramasastry, Code 551, of GSFC, will be the Principal Investigator of the proposed program.

The proposed program is included in the present GSFC plan for present and future VLBI experiments. Coordination and communication will be maintained with Dr. T. A. Clark, Space and Earth Science Division of GSFC, who is the Goddard RTOP Manager for VLBI experiments. Coordination will also be maintained with the VLBI research groups at MIT, Lincoln Laboratory, JPL, NRAO. Dissemination of information will be made through NASA Technical Reports and journal articles.

d. Tentative Plans For The Future

Analysis of data from the experiments will continue into FY-1972. The following tasks are planned for the future.

d-1. Two and three base-line experiments will be conducted using ATS satellites and any of the following baseline configurations.

a. Mojave (ATSR) - Rosman (ATSR)

b. Rosman (ATSR) - Agassiz (SAO)

c. Agassiz (SAO) - Mojave (ATSR)

d. Rosman (ATSR) - Quito (ATSR)

e. Quito (ATSR) - Mojave (ATSR)

f. Santiago (STADAN) - Mojave (ATSR)

d-2. A transcontinental baseline experiment will be attempted using Rosman, USA (ATSR) - Kashima, Japan (ATSR) and Mojave, USA (ATSR) - Kashima, Japan (ATSR) baselines.

d-3. Work towards refinement of experimental and data processing techniques will be continued.

d-4. Data analysis system will be implemented for routine reduction of VLBI data and computation of orbits of ATS satellites.

The VLBI orbits will be compared with the orbits generated by the routine range and range-rate data collected at ATSR sites.

d-5. VLBI data will be used to study such geodetic problems as continental drift, polar motion, rotation of the earth's axis and the like.

d-6. Our immediate objective based on present experimental standards is to achieve;

d-6-1. Ephimeris for the ATS satellites with an accuracy of 0.5 meters or less.

d-6-2. Determination of the Earth's polar axis with an accuracy of 0.5 meters at 12 hour intervals.

d-6-3. Determination of the variations in the rate of rotation of the Earth to an accuracy of less than 1 msec or 0.5 meters at the equator.

Acknowledgements

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